Environmental Pollution 242 (2018) 1904–1911

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

A simple slash-and-char system to mitigate climate change and environmental pollution☆

Jie-Liang Liang [a, b], Wen-hua Zhou [b], Shao-ming Gao [b], Wan-peng Yu [b], Wen-sheng Shu [a], Jin-tian Li [a, b, *]

[a] School of Life Sciences, South China Normal University, Guangzhou, 510631, PR China
[b] School of Life Sciences, Sun Yat-Sen University, Guangzhou, 510275, PR China

ARTICLE INFO

Article history:
Received 2 February 2018
Received in revised form
10 July 2018
Accepted 17 July 2018
Available online 20 July 2018

Keywords:
Slash-and-char
Open-burning
Rice straw
Climate change mitigation
$PM_{2.5}$
Polycyclic aromatic hydrocarbons

ABSTRACT

Agriculture-based climate change mitigation may occur through enhancing the carbon sink or through reducing greenhouse gases (GHGs) emissions from agricultural residue treatment, as open burning of agricultural residues produces millions of tons of GHGs and air pollutants annually worldwide. Charring slashed biomass, termed as slash-and-char, has been considered as a promising alternative to open burning in dealing with agricultural residues such as rice straw. Previous studies, however, focused on relatively sophisticated slash-and-char systems, which could not be practiced easily by smallholder farmers in developing countries. Here we introduce a simple slash-and-char system to mitigate the environmental problems associated with open burning of rice straw. This system could convert 30.7% of the initial carbon in rice straw into biochar, much higher than that retained in the ash generated by open burning (3.95%). It could also cut GHGs, particulate matters and polycyclic aromatic hydrocarbons (PAHs) emissions by 26.9%, 99.0% and 99.4%, respectively. If open burning of rice straw was replaced by the slash-and-char, the annual emissions of GHGs, particulate matters and PAHs in China would decrease by at least 15.4 Tg, 1.51 Tg and 1.27 Gg, correspondingly. This decrease is nearly twice the size of China's estimated forest C sink (8.81 Tg).

1. Introduction

After China signed the Paris Agreement, questions arise about how to turn the promise into reality. Facing international pressures to control its CO_2 release, as well as domestically high levels of air pollutants, China needs to adopt new strategies for emission mitigation (Liu et al., 2013). One of the largest sources of atmospheric pollutant emissions comes from open burning of rice straw (Crutzen and Andreae, 1990; Levine et al., 1995; Andreae and Merlet, 2001; Liu et al., 2013). As the largest rice producer in the world (Lim et al., 2012), China's annual rice production in 2009 was about 197 million tons (Faostat, 2009), and the output is expected to remain high in the next few decades due to the economic and population growths. It is reported that, for every kilogram of harvested paddy, 0.41–3.96 kg of rice straw will be produced (Lim et al., 2012). In this way, rice production gives an estimation of about 81–780 Tg of rice straw produced per year in China. In fact, according to an extensive survey, the annual yield of rice straw in China was estimated as 175 Tg (Xu and Yang, 2010). Despite the variations between different estimations, it is no doubt that the yield of rice straw in China is extremely high.

To deal with such a great amount of rice straw, open burning has been widely practiced in China (about 24% of the total rice straw production), because it is a cheap disposal way to clear the surface biomass from land for faster crop rotation and to return some nutrients to paddy soils (Zhang et al., 2008a; Gadde et al., 2009). However, this common practice has adverse effects on global atmospheric chemistry, global climate change and human health (Crutzen and Andreae, 1990; Levine et al., 1995; Andreae and Merlet, 2001; Qu et al., 2012). It is estimated that the annual total emissions of CO_2 and CO from rice straw burning in China were about 48 Tg and 2 Tg, respectively (Ni et al., 2015). Additionally, a previous study showed that the total particulate matter less than 2.5 μm ($PM_{2.5}$) emissions from rice straw field burning in China was estimated as 428 Gg (Zhang et al., 2017). Furthermore, open

☆ This paper has been recommended for acceptance by Baoshan Xing.

* Corresponding author. School of Life Sciences, South China Normal University, Guangzhou 510631, PR China.
E-mail address: lijtian@mail.sysu.edu.cn (J.-t. Li).

https://doi.org/10.1016/j.envpol.2018.07.074
0269-7491/

burning of rice straw also leads to emissions of gaseous and particulate polycyclic aromatic hydrocarbons (PAHs), some of which have significant toxicological properties and are notably potential carcinogens (Zhang et al., 2008b).

One efficient way to mitigate climate change and comprehensively utilize straw is slash-and-char (i.e. converting crop straw into biochar), which provides great potential for mitigating carbon emission into the air, since biochar produced from slash-and-char can lock up most of the carbon from biomass feedstock in a much more durable form (Lehmann et al., 2007). Previous studies show that the soils generated by slash-and-char are generally characterized by a higher level of organic matter and a greater retention of cations than in the surrounding soils (Lehmann et al., 2003; Downie et al., 2011). Also, the application of biochar is demonstrated frequently to help to promote microbial abundance, diversity and activities by providing them with better soil conditions and more diverse and expanded niches (Gui et al., 2015). Nowadays, the traditional slash-and-char technique has been greatly improved as modern slash-and-char (i.e., pyrolysis-biochar) systems, which have been successfully used in some developed countries (Glaser, 2007; Meyer et al., 2011; Park et al., 2014). However, it should be noted that modern slash-and-char systems require a series of sophisticated facilities including the pyrolysis facility, feedstock pretreatment equipment, farming equipment as well as transportation vehicles (Roberts et al., 2010), which are financially unviable in many developing countries. Also, the direct costs for pyrolysis processes and indirect costs (including those for crop straw and biochar transportation) were estimated to be relatively high (Roberts et al., 2010).

In contrast, a traditional slash-and-char system is quite simple, which typically includes the following three procedures (1) cutting of the biomass above-ground (e.g. crop residues): as land clearance; (2) drying and charring the biomass on site with simple earthen mounds or pits; and (3) mixing the produced biochar with its surrounding soil, which is used for crop production subsequently (Lehmann et al., 2007; Niu et al., 2015). Biochar can be easily obtained on site and directly mixed with soils, without using sophisticated machines and without extra costs for biomass collection and transportation of biomass and biochar. The simplicity of this system allows immediate manual implementation by smallholder farmers, which makes it particularly attractive in many developing countries. Up to date, however, no efforts have been made to evaluate the potential of a slash-and-char system for dealing with crop straw in developing countries.

In this study, we compared carbon fixation potential, the gas and particulate emission factors and the chemical compositions of $PM_{2.5}$ from open field burning and charring rice straw with a traditional slash-and-char system. Also, we investigated PAH concentrations in the soils before and after slash-and-char. Our results showed that the simple slash-and-char system offers new promise for more soil carbon sequestration, less carbon emissions and less environmental impacts. Furthermore, based on the published national and worldwide data on rice straw, we made an estimation of the reduced amounts of greenhouse gases (GHGs) and pollutants assuming that field burning was switched to a slash-and-char system. To our knowledge, this is the first field investigation of GHGs, particulates and pollutants emissions from charring rice straw with a traditional slash-and-char system.

2. Materials and methods

2.1. Study site

This experiment was performed on a farmland located in Guangzhou, the capital of Guangdong Province, China (23°06′N, 113°24′E). The experiment site was selected far away from highways or any point emission sources. The region is characterized by a subtropical monsoonal climate with an annual average temperature of about 20 °C and an annual average rainfall of about 1500 mm, which provides a suitable agricultural environment for continuous year-round rice cultivation. Farmers in the region cultivate two crops of rice each year, divided into spring and autumn seasonal periods. After rice harvest, a great amount of generated rice straw is usually left on site, which finally ends up in open burning.

2.2. Experiment design

The field experiment was conducted on sunny days from January 5th to January 8th, 2015. The temperature, wind speed and wind direction were determined prior to and during the experiment. It was recorded that the ambient air temperature was 18–23 °C and the wind speed was less than 2 m s^{-1}. Throughout the experiment, the wind speed and wind direction remained relatively steady. The ambient background levels were also measured. There were two experiment treatments (i.e. open field burning and slash-and-char) in this study. About a hundred kg of dry rice straw (moisture content < 5%) was collected from the farm, mixed thoroughly, and then divided into two halves. One half was used as biomass feedstock for field burning, and the other half was used for slash-and-char. The rice straw used in each treatment was weighed before experiment and a small bundle was collected and transported to the lab for further analysis.

In the open burning treatment, the rice straw was treated in a similar way as described by Li et al. (2007). Briefly, 45 kg of rice straw was spread equally in three windrows (i.e. three replicates for the treatment) in an open area of the farmland. The length and width of each windrow was about 4.6 and 1.0 m, respectively. The space between every two windrows was about 2.0 m, which was the same as the common windrow spacing for open burning (Li et al., 2007). That is, 15 kg of rice straw was burnt in each windrow and the area densities of the rice straw windrow were about 3 kg m^{-2}, which was similar to those of open burning in the field (Li et al., 2007). The headfire ignition technique (when a fire is started on the upwind side of a field) was adopted, simulating the common open field burning practice (Carroll et al., 1977; Li et al., 2007). After the burning in a windrow was finished, the next replicate was performed sequentially. As for the slash-and-char treatment, 54 kg of rice straw was used to construct three rice straw stacks (i.e. three replicates for the treatment; 18 kg of rice straw for each replicate) in an open area of the farmland. Briefly, the biomass feedstock was prepared as several rice straw bales (each with a length of 1.0 m, a width of 0.3 m and a height of 0.3 m). Each rice straw stack consisted of three layers and was stuffed with six rice straw bales (approximately 3 kg each). After construction, the rice straw stacks were covered with the surrounding soil to form 'biomass-soil' stacks (in the shape of a cone with a base diameter of approximately 2.3 m and a height of 1.0 m). Based on the practical experience of local farmers, a mass ratio of 1:25 biomass feedstock:soil (w/w) was used. According to the previous reports, the annual yield of rice straw is estimated as 20 t ha^{-1} (on a dry weight basis; Zhao et al., 2012), and the bulk soil density is about 1.2 g cm^{-3} (Zhang et al., 2005). In this situation, only the soil from the top 20 cm soil layer of approximately 10 m^2 of land is needed to employ the slash-and-char method to deal with the rice straw produced on 1000 m^2 of land. To start flaming fire in a 'biomass-soil' stack, each straw bale was ignited using ignition sticks at 600 °C for 5 min. In this study, we adopted and slightly improved a mature electrical heating ignition technique in order to obtain an ignition stick with the high-temperature electrical resistance inside and the stainless

steel jacket outside. The ignition stick can be repeatedly used for about 5000 times, which means that the total cost for every ignition process is less than 1 RMB by rough estimation. Several ignition sticks can be used simultaneously to improve the ignition and combustion efficiencies when it is necessary. Little smoke was released from the 'biomass-soil' stack as the burning process proceeded. After the smoldering in a 'biomass-soil' stack was finished (when no smoke could be seen), the next replicate was performed sequentially.

2.3. Sample collection

The gas and particulate sampling instruments, including a high-volume sampler, a middle-volume sampler and a gas bag, were set up on an agricultural vehicle with a sampling height of about 1.3 m above the ground. For detailed description of gas and particulate collection, please see Supporting Information. To collect smoke emissions efficiently, the vehicle was moved flexibly depending on the wind speed and wind direction. For the open burning treatment, the sampling site was about 2.0 m away from the fire, which was distant enough for gaseous and particulate emissions to dilute and cool to ambient temperature before being sampled. The sampling time for each replicate lasted about 22 min, including the burning and smoldering stages. The ash produced as well as the unburnt straw in each replicate were collected for weighing, and then a portion of both were sealed and brought back to the lab for carbon content determination.

For the slash-and-char treatment, the sampling instruments were located about 1.0 m from the downwind edge of a 'biomass-soil' stack to collect all the smoke produced during the flaming and smoldering processes, which lasted about 22 h. The majority of rice straw in the stack was converted into biochar and little ash was produced, which made it difficult to be separated from biochar. Therefore, the biochar/ash mixture was considered as biochar for the following analysis and calculation. It was observed that approximately 3 kg of rice straw in each 'biomass-soil' stack remained unburnt after the smoldering was finished, which meant that the burnt/charred biomasses of rice straw were the same in both open burning and slash-and-char treatments.

2.4. Gas and particulate analysis

A gas chromatography-flame ionization detection (GC-FID) was used to measure CO_2, CO and CH_4, which was described elsewhere (Yi et al., 2007; Wang et al., 2015). NMVOC were analyzed using an Entech 7100 Preconcentrator (Entech Instruments Inc., CA, USA) with an Agilent 5973 N gas chromatography-mass selective detector/flame ionization detector (GC-MSD/FID, Agilent Technologies, USA). The detailed procedures of sample analysis, standard preparation and sample calibration were reported previously (Yi et al., 2007; Wang et al., 2015). The ambient background levels at the sampling site were also measured.

A small piece (1.5×1.0 cm) of each quartz filter was used to determine organic carbon (OC) and elemental carbon (EC) in $PM_{2.5}$ using an OC/EC analyzer (Sunset Laboratory Inc., USA) using the NIOSH protocol as previous described (for details, see Supporting Information; Shen et al., 2012). For analysis of water-soluble inorganic ions in $PM_{2.5}$, about a quarter of each collected quartz filter was cut into small pieces, dissolved in distilled water, and then the solutions were collected and filtered by 0.45 μm membranes. Solution ions as K^+ and Cl^- were quantified using an ion chromatograph DX-600 (Dionex, USA). The heavy metals in $PM_{2.5}$ were determined by Elan 6000 inductively coupled plasma mass spectrometry (ICP-MS; Perkin Elmer, USA) as described elsewhere (Niu et al., 2015). Three blank filters were also analyzed, and the average of the blank concentrations was subtracted out when calculating the sample results.

2.5. PAHs extraction and analysis

PAHs extraction, preparation and analysis methods were described elsewhere (for details, see Supporting Information; Wang et al., 2012). The 16 parent PAHs identified as priority pollutants by both the US Environment Protection Agency and the European Union were included in this study: naphthalene (NAP), acenaphthylene (ACY), acenaphthene (ACE), fluorene (FLU), phenanthrene (PHE), anthracene (ANT), fluoranthene (FLA), pyrene (PYR), benz[*a*]anthracene (BaA), chrysene (CHR), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo[*a*]pyrene (BaP), dibenz[*a*,*h*]anthracene (DahA), indeno[l,2,3-cd]pyrene (IcdP), and benzo[*g*,*h*,*i*]perylene (BghiP). Hereafter, the 16 PAHs and 7 carcinogenic PAHs (namely BaA, CHR, BbF, BkF, BaP, IcdP, and DahA) were denoted as PAH16 and PAH7, respectively.

2.6. Calculation of emission factor

The emission factors were determined by carbon mass balance method (Zhang et al., 2000), which has been used widely to evaluate emission factors of CO_2, CO, CH_4, nonmethane hydrocarbons and particulate carbon species during open burning of a variety of biomass stocks (Lee et al., 2005; Li et al., 2007). It is assumed that all the burnt carbon is emitted into the atmosphere in the forms of carbonaceous gases and particulates (such as CO_2, CO, CH_4, NMVOC and $PM_{2.5}$) in this method, which is presented in the following equation:

$$C_f - C_a = C_{CO2} + C_{CO} + C_{CH4} + C_{NMVOC} + C_{PM}$$

Where C_f is the carbon mass in the biomass, and C_a is the carbon mass in the ash or that in the biochar. The carbon mass in CO_2, CO, CH_4, NMVOC and particulates are denoted as C_{CO2}, C_{CO}, C_{CH4}, C_{NMVOC}, and C_{PM}, respectively. OC and EC in $PM_{2.5}$ are used in the carbon mass calculation of particulates. Ambient background levels were subtracted out for calculation of emission factors for both open burning and slash-and-char. The sampling site in this study was relatively close to the fire; therefore, it is reasonable to neglect the physicochemical processes of gases and particulates in the atmosphere (Li et al., 2007). Furthermore, the biomass, ash and biochar were weighed, and the carbon contents in all of them were also analyzed. These data were used for the calculation of emission factors, which was expected to reduce the uncertainties associated with this approach.

2.7. Global warming potential assessment

The global warming potential (GWP) was used as a quantified measure of the globally relative radiative forcing impacts of certain GHGs compared to CO_2 over a chosen time horizon in the study (Permadi and Oanh, 2013). GWP of GHGs and the short-lived climate pollutants emitted from open burning and slash-and-char is assessed using CO_2-equivalent emissions summarized in previous studies (Roberts et al., 2010; Permadi and Oanh, 2013).

2.8. Statistical analysis

All statistical analyses were performed using SPSS version 18.0 software (SPSS, Chicago, USA). Unless otherwise stated, the shown significant differences between the open burning and slash-and-char treatments were tested by Welcoxon rank sum test.

3. Results and discussion

3.1. Carbon fixation by open burning and slash-and-char

The ash produced by open burning and the biochar by slash-and-char of 15 kg of rice straw was 2.30 ± 0.20 and 4.12 ± 1.28 kg, accounting for 15.3% and 27.3% of the biomass feedstock, respectively. It was reported that the ash yield of open burning of rice straw could vary from 10 to 17% of the biomass feedstock, depending on different biomass sources, field conditions, and so on (Binod et al., 2010; Roberts et al., 2010). That is, the ash yield of open burning in our study fell within the reported normal range. On the other hand, we recently employed a simple slash-and-char system to char rice straw and recorded the biochar yields of 10–15% (Niu et al., 2015). The variations between our prior and present studies could be attributed at least partially to the fact that different methods were used to construct 'biomass-soil' stacks for 'slash-and-char' systems and that rice straws were collected from two different sites. Nonetheless, the biochar yields of simple 'slash-and-char' systems were considerably lower than those (27%–48%) of sophisticated ones (Woolf et al., 2010).

On average, the carbon content of the rice straw (on a dry weight basis) used in our study was about 38.9%, falling within the range (36–52%) normally observed for rice straw in China (Liu et al., 2011; Chiang et al., 2013). The carbon content in the ash from the open burning treatment was about 12.0%, whereas the carbon content in the biochar from the slash-and-char treatment was as high as 43.8%. That is to say, only 4.73% of the initial carbon in the rice straw remained in the ash (soil) after open burning, and up to 95.3% of the carbon was emitted into the atmosphere (Fig. 1), being comparable to the previous results (Lehmann et al., 2006). In contrast, 30.7% of the initial carbon remained in the biochar from the slash-and-char and the remaining 69.3% was released into the atmosphere (Fig. 1). The carbon content in the biochar in this study was similar to that observed in a simple slash-and-char system reported before (Niu et al., 2015), but was lower than that of the biochar generated from sophisticated slash-and-char systems (49–100% depending on different pyrolysis processes) (Woolf et al., 2010).

3.2. Gaseous pollutant emissions from open burning and slash-and-char

In contrast to the carbon sequestration potentials, the gas and particulate emission reductions from the simple slash-and-char system compared with those from rice straw open burning has been less explored previously. In this study, emission factors of gaseous pollutants from open burning and slash-and-char were determined in parallel and are shown in Fig. 2 and Table S1. The average CO_2 emission factors from open burning was 1353 g kg^{-1} of the dry biomass, similar to the published results specific to open field burning of rice straw both in China and other countries, which ranges from 917 to 1674 g kg^{-1} (Table S1; Turn et al., 1997; McMeeking et al., 2009; Zhang et al., 2013; Ni et al., 2015; Zhang et al., 2017). In contrast, the emission factor of CO_2 from the simple slash-and-char treatment was 988 g kg^{-1}, which was about 27.0% lower than those for open burning of rice straw. Additionally, emission factors of CO and CH_4 from the open burning treatment were 3.50 and 0.36 g kg^{-1}, respectively. These values were significantly lower than those reported previously (Table S1). However, the variation in CO emission factors from open burning was 43.9%, which was comparable to those in the literature (4.78–45.5%; Table S1), and the variation in CH_4 emission factors was relatively small (5.56%) compared to previous study (91.7%; Table S1). The discrepancy could be explained at least partly by variables such as ignition techniques (headfire versus backfire when a fire is started downwind), burning temperature, oxygen contents during combustion, combustion efficiency, rice straw types, moisture contents and so on. The CO and CH_4 emission factors for the slash-and-char treatment were only 0.44 and 0.13 g kg^{-1}, respectively. It followed that the CO and CH_4 emission factors were decreased by 87.3% and 65.0% correspondingly, in comparison to those for the open burning treatment. Besides, the NMVOC emission factor for the slash-and-char treatment was 7.47 g kg^{-1}, being only 25.9% of that for the open burning treatment (28.8 g kg^{-1}). The significantly lower gas emissions may be largely owing to greater carbon stabilization potential of the simple slash-and-char treatment (Lehmann et al., 2006).

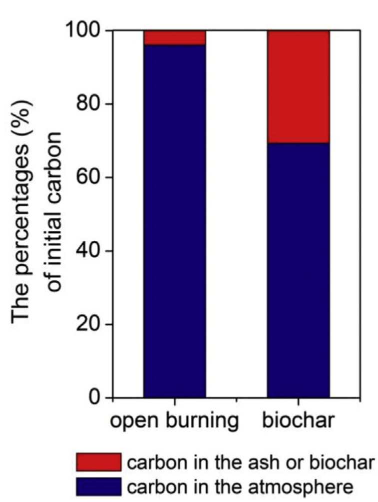

Fig. 1. The percentages of initial carbon in the rice straw feedstock that were emitted into the atmosphere or remained in the ash or biochar, respectively. The results are given as means ($n = 3$).

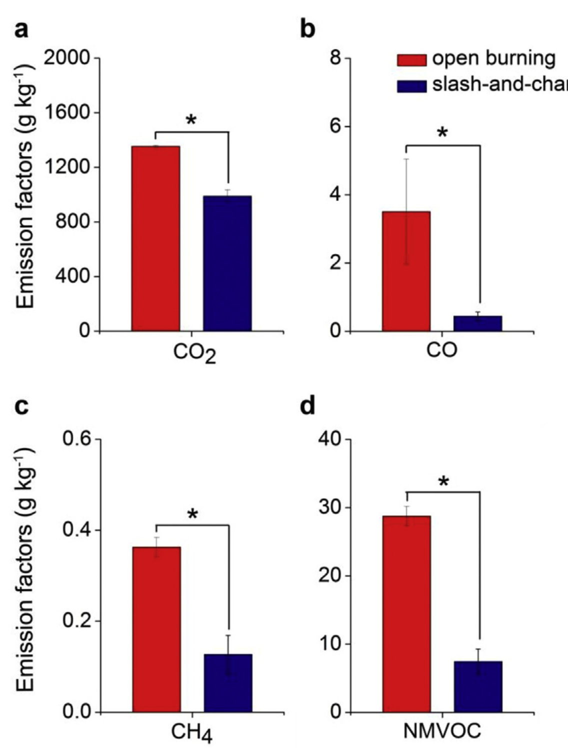

Fig. 2. Emission factors (g kg^{-1}) of CO_2 (a), CH_4 (b), CO (c) and NMVOC (d) from open burning and slash-and-char of the rice straw feedstock. The results are given as means ± SE (n = 3). *, $P < 0.05$.

Carbon emissions were dominated by CO_2, which accounted for 94.9% and 69.3% of carbon content in rice straw from open burning and slash-and-char, respectively, with CO contributing 0.386% and 0.049%, and CH_4 contributing 0.070% and 0.024%. The percentages of CO_2 and CH_4 in the gaseous emissions from rice straw open field burning were comparable to those reported in the literature, while the percentage of CO was lower (Jenkins and Bhatnagar, 1991; Zhang et al., 2008a; Gadde et al., 2009). The modified combustion efficiency was 0.99 for open burning and slash-and-char.

3.3. Particulate pollutant emissions from open burning and slash-and-char

The emission factors of TSP and $PM_{2.5}$ from open burning were 21.7 and 14.4 g kg^{-1} respectively (Fig. 3 and Table S1). The $PM_{2.5}$ emission factor from open burning was comparable with the values (12.9, 12.1 and 13.1 g kg^{-1}) for rice straw burning in China and in USA reported before (Hays et al., 2005; Zhang et al., 2013, 2017). Remarkably, the emission factors of TSP and $PM_{2.5}$ from the slash-and-char treatment were as low as 0.42 and 0.14 g kg^{-1}, respectively. These results suggested that the TSP and $PM_{2.5}$ emissions were decreased by 98.1% and 99.0% if the open burning was switched to the slash-and-char.

For carbon emissions of $PM_{2.5}$ from the open burning, OC emission factor was 5.95 g kg^{-1} and EC emission factor was 0.11 g kg^{-1}, which fell in the ranges (0.9–10.5 g kg^{-1} for OC and 0.17–1.38 g kg^{-1} for EC) reported in previous studies (Table S1). Both OC and EC emission factors of $PM_{2.5}$ from the slash-and-char were 0.02 g kg^{-1} and 0.0009 g kg^{-1}, being approximately 1% of those of the open burning (Fig. 4). As for other components in $PM_{2.5}$, Cl^- and K^+ from the open burning has the second and third largest emission factors (2.68 and 1.54 g kg^{-1}, respectively), which were comparable with those reported in a previous study (Hays et al., 2005). Meanwhile, the emission factors of these components from the slash-and-char (0.011 g kg^{-1} for Cl^- and 0.006 g kg^{-1} for K^+) were reduced by about 99% compared to those of the open burning (Fig. 4). The low emission factor of K^+ from the slash-and-char was consistent with our observation that little smoke was released during the slash-and-char process, considering that K^+ is often used as a tracer for biomass smoke. In addition, the emission factors of Pb, Zn, Cu, Cd and As in $PM_{2.5}$ were also determined and displayed in Table S2. The emission factors of the heavy metals from the slash-and-char were only about 1% of those of the open burning.

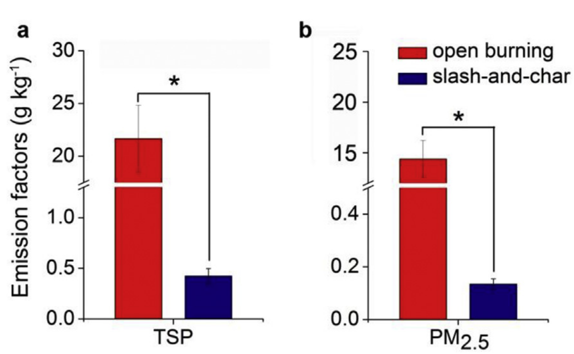

Fig. 3. Emission factors (g kg^{-1}) of TSP (a) and $PM_{2.5}$ (b) from open burning and slash-and-char of the rice straw feedstock. The results are given as means ± SE (n = 3). *, P < 0.05.

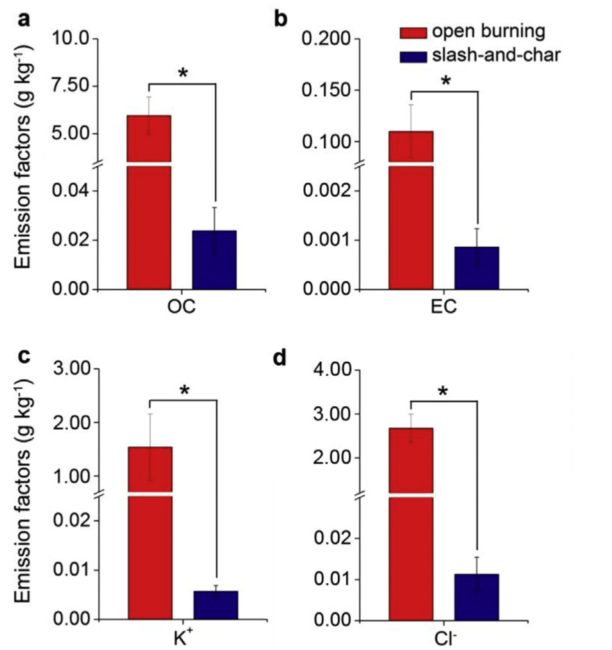

Fig. 4. Emission factors (g kg^{-1}) of major components in $PM_{2.5}$ from open burning and slash-and-char of the rice straw feedstock. The results are given as means ± SE (n = 3). *, P < 0.05.

3.4. Chemical compositions of $PM_{2.5}$ emissions from open burning and slash-and-char

Results of chemical analyses of $PM_{2.5}$ emissions from the two treatments were presented in Table 1. As it is known from earlier studies that the majority of $PM_{2.5}$ (about 50%) emission from crop residue combustion is carbonaceous aerosol (Turn et al., 1997), our results were consistent with the previous finding. The carbonaceous composition was dominant in the $PM_{2.5}$ mass, accounting for about 42.5% and 17.5% of total $PM_{2.5}$ mass from open burning and slash-and-char, respectively. Specifically, OC content from the slash-and-char (16.9%) was only 40% of that from the open burning (41.8%), while EC content showed no significant differences between these two treatments. Our results showed that the slash-and-char system could significantly reduce the OC content in $PM_{2.5}$. For water soluble species, Cl^- and K^+ are an important anion and cation in $PM_{2.5}$ from open field burning of agricultural residues, respectively (Hays et al., 2005; Li et al., 2007). Our results showed that Cl^- and K^+ accounted for 12.8% and 9.90% of $PM_{2.5}$ from the

Table 1
Chemical compositions of $PM_{2.5}$ emitted from open burning and slash-and-char (wt % of $PM_{2.5}$ mass).

Chemical species	Open burning	Slash-and-char
OC	41.0 ± 1.64	16.3 ± 5.07
EC	0.74 ± 0.09	0.62 ± 0.23
Cl^-	16.7 ± 0.869	8.05 ± 2.13
K^+	9.89 ± 3.11	4.16 ± 0.49
Cd	(13.3 ± 4.61) × 10^{-7}	(5.38 ± 5.38) × 10^{-7}
Cu	(11.2 ± 6.63) × 10^{-6}	(46.6 ± 7.75) × 10^{-6}
Zn	(80.0 ± 29.6) × 10^{-6}	(25.0 ± 23.9) × 10^{-6}
Pb	(3.42 ± 1.01) × 10^{-6}	(5.72 ± 3.30) × 10^{-6}
As	(1.60 ± 0.57) × 10^{-6}	(1.05 ± 1.05) × 10^{-6}

Notes: The results are given as average weigh percent of $PM_{2.5}$ mass and SE (n = 3).

open burning, and for 8.10% and 4.16% of that from the slash-and-char.

3.5. PAHs emissions from open burning and slash-and-char

As most PAHs compounds studied are semivolatile and can distribute between gaseous and particulate phases, the emission factors corresponding to both the gaseous and particulate PAH16 were calculated (Fig. 5), while the emission factors for individual PAH were provided in Figs. S1 and S2. The emission factor of PAH16 from the open burning was 30.2 mg kg^{-1} (Table S1), which was within the normal range of 5.04–49.3 mg kg^{-1} reported in the literature for that of open field burning of rice straw (Jenkins et al., 1996). In contrast, the emission factor of PAH16 from slash-and-char was 0.188 mg kg^{-1}, which suggested a 99.4% reduction of the PAHs emission from the open burning.

The total emission factor for PAH16 distributed in gaseous phase was 26.4 ± 7.55 mg kg^{-1} for the open burning, accounting for 87.4% of total PAH16 emissions in the treatment. Although the emission factors of gaseous PAH16 for the slash-and-char also accounted for 91.0% of its total PAHs emissions, the total emission factor (0.171 ± 0.041 mg kg^{-1}) was significantly lower than that for the open burning (a 99.4% reduction; $P < 0.05$). In the case of PAH7 (BaA, CHR, BbF, BkF, BaP, IcdP and DahA), the total PAH7 was 1.66 mg kg^{-1} for the open burning and they mainly distributed in the particulate phase, accounting for around 89.6% of the total PAH7 emission. Meanwhile, the total PAH7 emission was only 0.012 mg kg^{-1} for the slash-and-char, which suggested a 93.0% decrease compared with that of open burning. Since PAHs can be easily attached to organic carbon (Kalmykova et al., 2013), the significant reductions in PAH emissions for the slash-and-char could be possibly due to more carbon sequestration in biochar. Previous study reported that open straw burning contributed 2.4% of the total emissions of PAH16 in China (Zhang et al., 2008b), the PAH16 emissions would be significantly reduced if slash-and-char replaced open burning.

3.6. PAHs in soil before and after slash-and-char

The concentration of PAH16 in soils before and after the slash-and-char was 209 ± 15.8 and 201 ± 22.1 μg kg^{-1}, respectively, making the soil weakly contaminated according to the common criteria (non-contaminated, < 200 μg kg^{-1}; weakly contaminated, 200–600 μg kg^{-1}) (Maliszewska-Kordybach, 1996). There was no significant difference ($P > 0.05$) in PAH16 concentration between the two soils. However, this was not the case for the concentrations of individual PAHs. Low molecular weight PAHs with two or three benzene rings (including NAP, ACE, FLU, ANT and PHE) were present in the treated soil at significantly ($P < 0.05$) increased levels, while the opposite was true for those with four to seven benzene rings like BbF, BkF, BaP, IcdP, DahA and BghiP (Fig. S3). It is well-recognized that the low molecular weight PAHs are easier to be degraded than those of high molecular weight. Therefore, the slash-and-char system shows the potential to mitigate soil PAHs contamination from field open burning of rice straw.

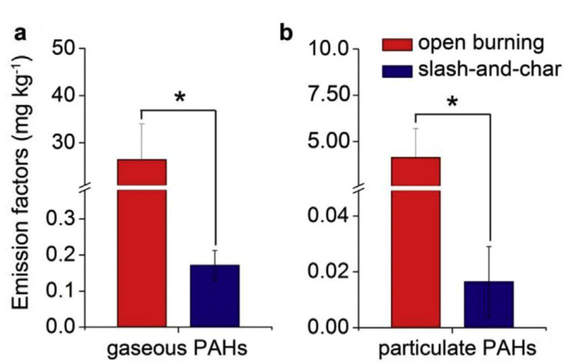

Fig. 5. Emission factors (mg kg^{-1}) of gaseous (a) and particulate (b) PAH16 from open burning and slash-and-char of the rice straw feedstock. The results are given as means ± SE ($n = 3$). *, $P < 0.05$.

3.7. Reduced emission of greenhouse gases, particles and pollutants

The total amount of rice residue produced annually in China was estimated to be about 175 Tg (Xu and Yang, 2010), and the estimated percentage of the amount of rice straw burnt in the field was approximately 24% (Zhang et al., 2008a). Therefore, the amount of rice straw treated by open burning in China could be as high as 42 Tg per year. According to the newly determined emission factors from the open burning and slash-and-char in this study, the reduced amounts of gaseous and particulate pollutants were calculated (Table 2). If the open burning was replaced by the slash-and-char, the GHGs emissions (considering only CO_2 and CH_4) in China would be reduced by up to 15.4 Tg (ranging from 12.4 to 19.8 Tg) per year, which is nearly twice the size of China's estimated forest C sink (8.81 Tg; Hu and Liu, 2006). Based on the literature of emissions in China, the emissions from crop straw field burning contributing to the total national anthropogenic emission has been estimated to be as follows: CO_2 (6.13%), CO (7.71%), CH_4 (0.68%) and PM (11.5%) (Streets et al., 2003; Cao et al., 2008). In addition, rice straw accounts for 18% in crop residues produced annually in China (Cao et al., 2008). Thus the emissions of these pollutants from rice straw open burning contribute a significant part to the total anthropogenic emissions. If the open burning of rice straw was replaced by the slash-and-char, about 0.30%, 1.21%, 0.10% and 2.03% of annual total anthropogenic CO_2, CO, CH_4 and PM emissions in China would be avoided. Such a reduction is also significant on a global scale. Rice residues available for open field burning were considered as 220–280 Tg in the world annually (Woolf et al., 2010). If the slash-and-char was applied to replace of the open burning, the reduced CO_2 and CH_4 emissions worldwide would be 80–102 and 0.11–0.14 Tg per year, respectively. In addition, those figures for $PM_{2.5}$ and PAHs would be 304–387 and 665–847 Tg annually. However, such emission estimation should be taken into consideration with some caution due to not only the uncertainties in emission factors (Table 2) but also other factors like variations in combustion efficiency and other properties of rice straws from different sources.

Furthermore, we used emission reductions of GHGs and short-lived climate pollutants to evaluate 20-year and 100-year GWP of the shift of the open burning of rice straw to the slash-and-char (Table 3). The CO_2 emissions reduction was excluded for it is reabsorbed as carbon biomass via photosynthesis in the next round of cultivation. The reduced GWP of warming agents in China was 4.88–7.82 (20-year) and 4.97–18.6 (100-year) Tg CO_2 equivalents, while on a global scale the reduced GWP was about 95.3–334 (20-year) and 29.5–111 (100-year) Tg CO_2 equivalents. The GWP of global biomass open burning estimated using the data from GFED 3 for 2007 (CO_2, CO, CH_4, NMVOC and black carbon (BC)) was around 13,992 (20-year) and 9159 (100-year) Tg CO_2 equivalents (Permadi and Oanh, 2013). In this case, the contributions from the global GWP reduction were about 0.681–2.39% (20-year) and 0.322–1.21% (100-year). If we considered the reduced emissions of CO_2, the GWP reduction associated with the shift would be higher. Note also that the reduced emissions of OC were calculated but excluded in the analysis of GWP, since the GWP value would be negative if it was included. Such a negative GWP value seemed to be a bit different

Table 2
Estimated annual emissions (Tg) of gaseous and particulate pollutants produced from open burning and slash-and-char of rice straw in China.

Pollutants	Open burning (Tg)	Slash-and-char (Tg)	Reduced amount[a] (Tg)	Reduced proportion[b] (%)
CO_2	56.3–57.2 (56.8)	37.7–43.9 (41.5)	12.4–19.5 (15.3)	22.0–34.1 (26.9)
CO	0.067–0.275 (0.150)	0.013–0.029 (0.018)	0.038–0.262 (0.132)	43.3–95.3 (87.3)
CH_4	0.014–0.047 (0.015)	0.002–0.008 (0.005)	0.006–0.045 (0.010)	42.9–95.7 (66.7)
NMVOC	1.15–3.43 (1.21)	0.161–0.406 (0.314)	0.744–3.27 (0.896)	64.7–95.3 (74.1)
$PM_{2.5}$	0.468–0.735 (0.605)	0.004–0.007 (0.006)	0.461–0.731 (0.599)	98.5–99.5 (99.0)
TSP	0.717–1.165 (0.911)	0.013–0.024 (0.018)	0.693–1.152 (0.893)	96.7–98.9 (98.0)
OC	0.184–0.326 (0.250)	0.286–1.64 × 10^{-3} (1.01 × 10^{-3})	0.182–0.325 (0.249)	99.1–99.9 (99.6)
EC	(2.94–6.30) × 10^{-3} (4.62 × 10^{-3})	(1.55–6.72) × 10^{-5} (3.78 × 10^{-5})	(2.87–4.60) × 10^{-3} (4.58 × 10^{-3})	97.6–99.6 (99.2)
PAHs	(0.640–1.89) × 10^{-3} (1.27 × 10^{-3})	(5.04–12.3) × 10^{-6} (7.90 × 10^{-6})	(0.628–1.88) × 10^{-3} (1.26 × 10^{-3})	98.1–99.5 (99.4)

Notes: Values presented in the brackets are average values.
[a] Reduced amount = Open burning − Slash-and-char.
[b] Reduced proportion = 1−Slash-and-char/Open burning.

Table 3
GWP of reduced emissions of GHGs and short-lived climate pollutants.

Species	National estimate, Tg y^{-1}			Global estimate, Tg y^{-1}		
	Reduced Emission (Tg y^{-1})	CO_2 equivalent (20 year)	CO_2 equivalent (100 year)	Reduced Emission (Tg y^{-1})[a]	CO_2 equivalent (20 year)	CO_2 equivalent (100 year)
Global warming agents						
CO	0.038–0.262 (0.132)	0.274–1.89 (0.950)	0.087–0.603 (0.304)	0.226–1.56 (0.786)	1.63–11.2 (5.66)	0.520–3.59 (1.81)
CH_4	0.006–0.045 (0.010)	0.432–3.24 (0.720)	0.150–1.13 (0.250)	0.036–0.268 (0.125)	2.59–3.24 (9.00)	0.9–6.7 (3.13)
NMVOC	0.744–3.27 (0.896)	10.4–45.8 (12.6)	3.35–14.7 (4.03)	4.43–19.5 (5.33)	62.0–273 (74.6)	19.9–87.8 (24.0)
BC	(2.87–4.60) × 10^{-3} (4.58 × 10^{-3})	4.88–7.82 (7.79)	1.38–2.21 (2.20)	(1.71–2.74) × 10^{-2} (2.73 × 10^{-2})	29.1–46.6 (46.3)	8.21–13.2 (13.1)
Total GWP		16.0–58.8 (22.1)	4.97–18.6 (6.78)		95.3–334 (136)	29.5–111 (42.0)

Notes: Values presented in the brackets are average values. The GWP values of different agents used for reduced emissions calculation are listed in Table S3 in Supporting Information. The BC values are calculated based on EC values.
[a] The average value of the amounts of rice residues (220–280 Tg) was used for global reduced emission calculation.

from that expected for rice straw open burning (Permadi and Oanh, 2013) and was probably due to relatively low emission factors of CO and CH_4 in the open burning compared to previous studies (McMeeking et al., 2009; Ni et al., 2015; Zhang et al., 2017). However, the estimation was just preliminary. The emissions of other pollutants like N_2O and SO_2 from field burning were not included in the study. Also, the avoided CO_2 equivalent emissions including agricultural emissions of N_2O and savings in fertilizer consumption associated with use of the biochar from slash-and-char on agricultural lands were not assessed.

4. Conclusions

Crop production in most developing countries usually generates a large quantity of residues which are usually field burnt after harvesting, causing adverse air quality and human health effects. Our results showed that the simple slash-and-char system possesses great potentials for mitigation of GHGs and air pollutants emissions. The significantly lower gas and particulate emissions might be due largely to the greater carbon stabilization potential of the simple slash-and-char treatment (Lehmann et al., 2006), while the significantly different carbon sequestration abilities between the two treatments might lie in the variations in temperature and oxygen contents during combustion. Since smallholder farming is very popular in many developing countries, where farmers prefer to deal with rice straw at a small scale, our proposed slash-and-char method is applicable in real world. Although our results were still preliminary, it suggested that slash-and-char to deal with crop straw might be one of the most promising pathways for China towards the goals of a sustainable and low-carbon country.

It should be noted, however, that further studies are needed to assess the generality of our results. First of all, more field experiments are necessary to explore the variations of the efficiency of this simple slash-and-char system in relation to geographically different sites. Secondly, it is also essential to determine the extent to which our results can be applicable to other major crop residuals, like wheat straw and corn stover. Thirdly, a comprehensive assessment of the simple slash-and-char system concerning its energetic, economic and climate change potentials will be required to further verify the applicability of this system. Additionally, although there are a few investigations about the use of slash-and-char for soil fertility improvement and pollution remediation, the effects of slash-and-char on soil microorganisms should also be investigated. Finally, further development and improvement of this simple system is needed for its potential large-scale applications around the world (especially in the developing countries).

Competing financial interests

The authors declare no conflict of interest.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Nos. 41622106, 31600082, U1501232, 2016A030312003 and C031001).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2018.07.074.

References

Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochem. Cycles 15, 955–966.

Binod, P., Sindhu, R., Singhania, R.R., Vikram, S., Devi, L., Nagalakshmi, S., Kurien, N., Sukumaran, R.K., Pandey, A., 2010. Bioethanol production from rice straw: an overview. Bioresour. Technol. 101, 4767–4774.

Cao, G., Zhang, X., Wang, Y., Zheng, F., 2008. Estimation of emissions from field burning of crop straw in China. Chin. Sci. Bull. 53, 784–790.

Carroll, J.J., Miller, G.E., Thompson, J.F., Darley, E.F., 1977. The dependence of open field burning emissions and plume concentrations on meteorology, field conditions and ignition technique. Atmos. Environ. 11, 1037–1050.

Chiang, K.Y., Lin, Y.X., Lu, C.H., Chien, K.L., Lin, M.H., Wu, C.C., Ton, S.S., Chen, J.L., 2013. Gasification of rice straw in an updraft gasifier using water purification sludge containing Fe/Mn as a catalyst. Int. J. Hydrogen Energy 38, 12318–12324.

Crutzen, P.J., Andreae, M.O., 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250, 1669–1678.

Downie, A.E., Van Zwieten, L., Smernik, R.J., Morris, S., Munroe, P.R., 2011. *Terra Preta Australis*: reassessing the carbon storage capacity of temperate soils. Agric. Ecosyst. Environ. 140, 137–147.

Faostat, F., 2009. Food and Agriculture Organization of the United Nations. Statistical databases.

Gadde, B., Bonnet, S., Menke, C., Garivait, S., 2009. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ. Pollut. 157, 1554–1558.

Glaser, B., 2007. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philos. T. R. Soc. B. 362, 187–196.

Gui, S., Whalen, J.K., Thomas, B.W., Sachdeva, V., Deng, H., 2015. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agric. Ecosyst. Environ. 206, 46–59.

Hays, M.D., Fine, P.M., Geron, C.D., Kleeman, M.J., Gullett, B.K., 2005. Open burning of agricultural biomass: physical and chemical properties of particle-phase emissions. Atmos. Environ. 39, 6747–6764.

Hu, H., Liu, G., 2006. Carbon sequestration of China's national natural forest protection project. Acta Ecol. Sin. 26, 291–296.

Jenkins, B., Bhatnagar, A., 1991. On the electric power potential from paddy straw in the Punjab and the optimal size of the power generation station. Bioresour. Technol. 37, 35–41.

Jenkins, B.M., Jones, A.D., Turn, S.Q., Williams, R.B., 1996. Emission factors for polycyclic aromatic hydrocarbons from biomass burning. Environ. Sci. Technol. 30, 2462–2469.

Kalmykova, Y., Bjorklund, K., Stromvall, A.M., Blom, L., 2013. Partitioning of polycyclic aromatic hydrocarbons, alkylphenols, bisphenol A and phthalates in landfill leachates and stormwater. Water Res. 47, 1317–1328.

Lee, S., Baumann, K., Schauer, J.J., Sheesley, R.J., Naeher, L.P., Meinardi, S., Blake, D.R., Edgerton, E.S., Russell, A.G., Clements, M., 2005. Gaseous and particulate emissions from prescribed burning in Georgia. Environ. Sci. Technol. 39, 9049–9056.

Lehmann, J., da Silva Jr., J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems–a review. Mitig. Adapt. Strat. Gl. 11, 395–419.

Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I., 2007. Amazonian Dark Earths: Origin Properties Management. Springer Science & Business Media.

Levine, J.S., Cofer III, W.R., Cahoon Jr., D.R., Winstead, E.L., 1995. Biomass burning: a driver for global change. Environ. Sci. Technol. 29, 120A-5A.

Li, X., Wang, S., Duan, L., Hao, J., Li, C., Chen, Y., Yang, L., 2007. Particulate and trace gas emissions from open burning of wheat straw and corn stover in China. Environ. Sci. Technol. 41, 6052–6058.

Lim, J.S., Manan, Z.A., Alwi, S.R.W., Hashim, H., 2012. A review on utilization of biomass from rice industry as a source of renewable energy. Renew. Sustain. Energy Rev. 16, 3084–3094.

Liu, Z., Guan, D., Crawford-Brown, D., Zhang, Q., He, K., Liu, J., 2013. Energy policy: a low-carbon road map for China. Nature 500, 143–145.

Liu, Z., Xu, A., Long, B., 2011. Energy from combustion of rice straw: status and challenges to China. Energy Power Eng. 3, 325–331.

Maliszewska-Kordybach, B., 1996. Polycyclic aromatic hydrocarbons in agricultural soils in Poland: preliminary proposals for criteria to evaluate the level of soil contamination. Appl. Geochem. 11, 121–127.

McMeeking, G.R., Kreidenweis, S.M., Baker, S., Carrico, C.M., Chow, J.C., Collett, J.L., Hao, W.M., Holden, A.S., Kirchstetter, T.W., Malm, W.C., Moosmuller, H., Sullivan, A.P., Wold, C.E., 2009. Emissions of trace gases and aerosols during the open combustion of biomass in the laboratory. J. Geophys. Res. Atmos. 114, 1–20.

Meyer, S., Glaser, B., Quicker, P., 2011. Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ. Sci. Technol. 45, 9473–9483.

Ni, H.Y., Han, Y.M., Cao, J.J., Chen, L.W.A., Tian, J., Wang, X.L., Chow, J.C., Watson, J.G., Wang, Q.Y., Wang, P., Li, H., Huang, R.J., 2015. Emission characteristics of carbonaceous particles and trace gases from open burning of crop residues in China. Atmos. Environ. 123, 399–406.

Niu, L.Q., Jia, P., Li, S.P., Kuang, J.L., He, X.X., Zhou, W.H., Liao, B., Shu, W.S., Li, J.T., 2015. Slash-and-char: an ancient agricultural technique holds new promise for management of soils contaminated by Cd, Pb and Zn. Environ. Pollut. 205, 333–339.

Park, J., Lee, Y., Ryu, C., Park, Y.-K., 2014. Slow pyrolysis of rice straw: analysis of products properties, carbon and energy yields. Bioresour. Technol. 155, 63–70.

Permadi, D.A., Oanh, N.T.K., 2013. Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact. Atmos. Environ. 78, 250–258.

Qu, C., Li, B., Wu, H., Giesy, J.P., 2012. Controlling air pollution from straw burning in China calls for efficient recycling. Environ. Sci. Technol. 46, 7934–7936.

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ. Sci. Technol. 44, 827–833.

Shen, G.F., Wei, S.Y., Wei, W., Zhang, Y.Y., Min, Y.J., Wang, B., Wang, R., Li, W., Shen, H.Z., Huang, Y., Yang, Y.F., Wang, W., Wang, X.L., Wang, X.J., Tao, S., 2012. Emission factors, size distributions, and emission inventories of carbonaceous particulate matter from residential wood combustion in rural China. Environ. Sci. Technol. 46, 4207–4214.

Streets, D.G., Bond, T., Carmichael, G., Fernandes, S., Fu, Q., He, D., Klimont, Z., Nelson, S., Tsai, N., Wang, M.Q., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. 108, 1–23.

Turn, S., Jenkins, B., Chow, J., Pritchett, L., Campbell, D., Cahill, T., Whalen, S., 1997. Elemental characterization of particulate matter emitted from biomass burning: wind tunnel derived source profiles for herbaceous and wood fuels. J. Geophys. Res. 102, 3683–3699.

Wang, R., Wu, T., Dai, W., Liu, H., Zhao, J., Wang, X., Huang, F., Wang, Z., Shi, C., 2015. Effects of straw return on C2–C5 non-methane hydrocarbon (NMHC) emissions from agricultural soils. Atmos. Environ. 100, 210–217.

Wang, Y., Tian, Z., Zhu, H., Cheng, Z., Kang, M., Luo, C., Li, J., Zhang, G., 2012. Polycyclic aromatic hydrocarbons (PAHs) in soils and vegetation near an e-waste recycling site in South China: concentration, distribution, source, and risk assessment. Sci. Total Environ. 439, 187–193.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nat. Commun. 1, 1–9, 56.

Xu, J., Yang, Q., 2010. Isolation and characterization of rice straw degrading *Streptomyces griseorubens* C-5. Biodegradation 21, 107–116.

Yi, Z., Wang, X., Sheng, G., Zhang, D., Zhou, G., Fu, J., 2007. Soil uptake of carbonyl sulfide in subtropical forests with different successional stages in south China. J. Geophys. Res. 112, 1–11.

Zhang, C., Tian, H.Q., Liu, J.Y., Wang, S.Q., Liu, M.L., Pan, S.F., Shi, X.Z., 2005. Pools and distributions of soil phosphorus in China. Global Biogeochem. Cycles 19, 1–8.

Zhang, H., Ye, X., Cheng, T., Chen, J., Yang, X., Wang, L., Zhang, R., 2008a. A laboratory study of agricultural crop residue combustion in China: emission factors and emission inventory. Atmos. Environ. 42, 8432–8441.

Zhang, H.F., Hu, J., Qi, Y.X., Li, C.L., Chen, J.M., Wang, X.M., He, J.W., Wang, S.X., Hao, J.M., Zhang, L.L., Zhang, L.J., Zhang, Y.X., Li, R.K., Wang, S.L., Chai, F.H., 2017. Emission characterization, environmental impact, and control measure of $PM_{2.5}$ emitted from agricultural crop residue burning in China. J. Clean. Prod. 149, 629–635.

Zhang, J., Smith, K., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M., Rasmussen, R., Thorneloe, S., 2000. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmos. Environ. 34, 4537–4549.

Zhang, Y., Dou, H., Chang, B., Wei, Z., Qiu, W., Liu, S., Liu, W., Tao, S., 2008b. Emission of polycyclic aromatic hydrocarbons from indoor straw burning and emission inventory updating in China. Ann. NY Acad. Sci. 1140, 218–227.

Zhang, Y.S., Shao, M., Lin, Y., Luan, S.J., Mao, N., Chen, W.T., Wang, M., 2013. Emission inventory of carbonaceous pollutants from biomass burning in the Pearl River Delta Region, China. Atmos. Environ. 76, 189–199.

Zhao, X., Zhou, Y., Wang, S.Q., Xing, G.X., Shi, W.M., Xu, R.K., Zhu, Z.L., 2012. Nitrogen balance in a highly fertilized rice-wheat double-cropping system in Southern China. Soil Sci. Soc. Am. J. 76, 1068–1078.